The Effects of Neutron Irradiation on Gamma Sensitivity of Linear Integrated Circuits

Jerry Gorelick[1], Ray Ladbury[2] and Lina Kanchawa[1]
[1]Boeing Satellite Systems, Los Angeles CA
[2]Orbital Sciences Corp/NASA-GSFC

Abstract: **A dozen linear bipolar microcircuits were first irradiated with neutrons then gammas and compared to the same devices exposed to gammas only. The data show that neutron irradiation can affect subsequent total dose behavior. This has significant hardness assurance implications.**

I. Introduction

It has been a common practice to decouple total ionizing dose (TID) effects from non-ionizing or displacement damage. This practice assumes the effects are independent and can be characterized separately [1], [2], with TID usually simulated with gammas from a cobalt source and displacement damage simulated with reactor neutrons. It has also been common during radiation lot acceptance testing to expose devices first to neutrons and then to TID. Recent research [3], [4] calls into question whether these effects can be decoupled. In this study, data on 12 different linear integrated circuits were reviewed, Table 1. For a number of devices TID degradation was the same whether they were first neutron irradiated or not. However, for half of the parts in the study, neutron exposure significantly affected the subsequent total dose degradation, see Figures 1-6. In these cases, one cannot decouple the effects of ionizing and non-ionizing radiation and a different approach to lot acceptance testing is required.

There have been several studies of proton versus gamma and neutron degradation [3]-[8]. Different devices exhibit different degradation mechanisms for input bias current, depending on their design and construction. In this work we see a wide variety of behavior including some large variations in trends from one lot to another.

J. Gorelick is with Boeing Satellite Systems, Los Angeles, CA 90009 USA (telephone: 310-364-8585, e-mail: jerry.l.gorelick @boeing.com)
R. Ladbury is with Orbital Sciences/GSFC, Mt. Airy MD 21771 USA (telephone: 301-286-1030, email: rladbury@ pop500.gsfc.nasa.gov)
L. Kanachawa is with Boeing Satellite Systems, Los Angeles, CA 90009 USA (telephone: 310 – 416-6243 email: lina.a.kanchawa@boeing. com)

II. Test Description

The current data were gathered in the course of normal radiation lot acceptance testing. Sample sizes ranged from four parts from a single wafer to as many as 22 parts from a single diffusion run. Total dose and neutron testing were done by the Raytheon Component Evaluation Center, El Segundo, Calif. Total dose exposures were made using their gammacell-200 cobalt-60 irradiator. Testing was done to Mil-Standard 883 Method 1019 at standard, 50 – 300 rads/s, exposure rates. All parts were biased during exposure, typically using a vendor burn-in circuit or similar scheme. Electrical testing was done on an LTS2020 linear tester or a Tektronix S3270. In all cases, parts were exposed to several total dose levels with electrical testing done immediately after each exposure. A complete set of electrical parameters were measured. However, in this study we only looked at input bias current, typically the most sensitive parameter.

Neutron exposures were conducted per Mil-Standard 883 Method 1017 using the Triga Reactor at the Pennsylvania State University. Parts were unbiased during exposure. In all cases only a single neutron exposure level was used. The specific level, anywhere from 4E11 to 6E12 neutrons/cm^2, differed depending on the subsequent total dose exposure levels and the program conducting the testing.

III. Test Results and Discussion

IIIA. General. Twelve different devices, op-amps and comparators, from three different vendors, were reviewed. See Table 1 for a list of devices and a summary of the results. Data were reviewed on at least two different diffusions for each device. All test samples were "space" level, bought to either an internal Specification Control Drawing [SCD], a Standard Microcircuit Drawing or a Mil-M38510 slash sheet. All samples were burned in prior to any testing. Date codes on the devices ranged from 92XX to 02XX.

Of the 12 devices, half exhibited some degree of modified TID sensitivity following neutron irradiation. In general we see a correlation between the magnitude of the neutron and TID shifts in bias current and whether neutron exposure affected subsequent TID sensitivity. Several of these devices are known to exhibit enhanced low dose rate [ELDRS] sensitivity. However, there was no obvious correlation between devices that exhibited decreased TID sensitivity and those that exhibit ELDRS. Any possible coupling between displacement damage and ELDRS is still to be determined.

With two exceptions, the OP-27 and OP-484, where shifts due to neutron irradiation were small compared to those from TID irradiation, little or no effect was observed. Where neutron degradation was large compared to TID induced shifts, the neutron irradiation history significantly affected subsequent TID behavior.

LM 111. This part is a low input current voltage comparator. The device uses substrate pnp transistors in the input stage, see [5]-[8] for a detailed discussion of the design and construction of the LM111. It exhibited the most pronounced affect of all the parts in this study. Devices that were exposed to gammas only showed an increase in bias current that started to saturate in the 30 to 50 krads(Si) range, Figure 1. Parts that were first neutron irradiated showed a radically different behavior. After exposure to 30 krads, they tracked the total dose only parts but with reduced shifts, about half the magnitude. At higher exposure levels the shift in bias current decreased. It continued to decrease eventually becoming large and in the opposite polarity from the initial exposures.

The two lots showed approximately a 2X difference in neutron induced shifts, ~340 nA for diffusion HA07A083 and ~ 670 nA for diffusion HA077E40. They also showed a similar difference in total dose sensitivity. The lot that exhibited the larger shifts from neutron irradiation also exhibited a quicker turnaround in subsequent total dose behavior clearly indicating that the magnitude of the decreased gains correlated with subsequent total dose behavior. Several other lots were also reviewed. These lots were neutron then total dose irradiated, but were not subjected to total dose only. They exhibited the same qualitative behavior as the lots in Figure 1.

These results are not surprising when reviewed in light of some of the testing and analysis that has been previously reported in the literature on this part. Large lot-to-lot variability in the LM111 has been noted before [7], [8]. Saturation in input bias current at moderate dose levels has also been previously reported (9). Barnaby (7), observed an initial rise in bias current with dose, followed by some recovery at much higher exposure levels. What we have observed is an extreme version of this behavior. The recovery on the neutron irradiated parts occurs after only a relatively low dose compared with the levels where it occurs for parts exposed only to gamma radiation.

The larger neutron effects on bias current are also consistent with other reported data (6,9). In these works 52 Mev proton and 2 Mev electron irradiations were compared to cobalt-60 gamma irradiation. Degradation of both the electron and proton irradiated parts were significantly greater than those exposed only to cobalt-60 gammas. Here, of course, displacement and ionization damage occurred concurrently. In this experiment parts that are first neutron irradiated are significantly degraded before any additional total dose effects. Transistor gains are already highly degraded prior to TID effects.

LM124. This is a quad, low power, high gain, internally frequency compensated op-amp. While it is built using the same processes and has the same manufacturer as the LM111, the circuit design is quite different [8]. In Figure 2, we see a decreased sensitivity for the neutron irradiated parts. One of the three lots was exposed to 6E11 n/cm^2 while the other two were exposed to 2E12 n/cm^2. The lot exposed to the lowest neutron fluence degraded less than the other two lots and exhibited a smaller decrease in subsequent TID sensitivity. The other two lots showed an almost 2:1 difference in neutron degradation [mean delta of 157 nA versus 291 nA]. The lot that showed that larger neutron induced shifts also showed the larger decrease in TID sensitivity.

Barnaby et al [3] also saw much greater input bias current degradation on the LM124 with neutrons then with x-rays, concluding that, "Degradation in the LM124 operational amplifier input bias current is primarily the result of displacement damage." However, they also noted that, "The sum of independent measurements of ionization and displacement damage is greater than the proton response…" This is consistent with our observation of reduced total dose degradation after neutron irradiation.

As noted earlier, this work is a review of existing data. At this juncture one would like to take samples from these lots and proton test them as well as to gamma followed by neutrons for comparison. The expected degradation in a concurrent environment will be heavily dependent on the ratio of displacement to ionization levels and can be expected to show lot-to-lot variability.

OP-27. This device is a low noise precision op-amp with a compensated input state using a lateral pnp current source. A more complete discussion of the circuit design is contained in [5]. This was one of the parts where total dose sensitivity was affected by neutron irradiation even though neutron induced shifts were much smaller than TID shifts, on the order of 10 to 30 nA after exposure to 1E12 n/cm^2. Reference [5] also concluded that ionization was dominant over displacement for this device.

The degradation of parts subject to neutron and dose and dose only, are qualitatively quite similar (see Figure 3). In all cases, parts that are exposed only to gammas degrade less than those that were first exposed to neutrons. This is exactly the opposite behavior of the other devices where neutron irradiation affected subsequent total dose sensitivity. While the effect is not large for this device, it is consistent across all lots reviewed. The relatively small degradation from neutrons, compared to some of the other parts in this study, resulted in a smaller affect in subsequent TID sensitivity.

OP-484. This is a quad, precision rail-to-rail amplifier. This device has the most varied behavior of all the parts that exhibited any effects (Figure 4). One lot showed a pronounced decrease in TID sensitivity following neutron irradiation. The second lot shows no affect at all. Subtracting out the neutron degradation, the two sets of parts exhibit identical total dose shifts. Curiously the lot that showed the most neutron degradation (about 25% higher shifts, 170 nA versus 130 nA) was the lot that showed no subsequent reduction in TID sensitivity. These results are more disturbing than those that show consistent behavior across several lots.

These data suggest that a single lot may not be adequate to determine if there is synergistic behavior between neutron and gamma irradiations. The date codes of the two lots differ by three years. However, there were no known process changes. The vastly different behavior for the two test samples could lead to very different predictions of on-orbit behavior

RH1014. This is a quad precision op-amp. This device exhibits qualitatively consistent behavior though there is a large spread in the magnitude of the effects (see Figure 5). The neutron shifts were quite similar for all three lots (~ 90 to 100 nA increase over pre-rad). For two of the three lots, the total dose only parts exhibited about twice the shift at 200 krads as the parts that were first neutron irradiated. The third lot, however, exhibited a much more pronounced difference in the two sets of parts.

RH1056. This is a J-FET input precision op-amp. This was one of two FET input devices examined. The other such device, OP15/16 did not exhibit any decreased TID sensitivity. The pre-rad spec limit for input bias current is much lower for this device than the others, 0.05nA maximum. There was a 2:1 difference in the mean shifts due to neutron irradiation, ~0.06 vs. 0.12 nA. Like the OP-484, this part shows a significant variation between the two lots tested (see Figure 6). One lot showed little effect up to 100 krads. At higher levels, the total dose only set of parts exhibited a steady increase in bias current while the parts that were first neutron irradiated showed a much smaller increase.

The second lot, which showed the larger shift due to neutron irradiation, exhibits significantly different behavior. Degradation in bias current was much smaller for this lot than the other one. The neutron irradiated samples also show a change in direction of bias current versus the total dose only lot. This is similar, though not nearly as pronounced as all the LM111 lots reviewed in [5].

IV. Conclusions

For half of the parts reviewed, there appear to be no synergistic effects of ionization and displacement damage. The total dose degradation of devices is not affected by neutron irradiation. For the other half of the devices, however, this is not the case. Neutron exposures had anywhere from a mild to a pronounced effect on subsequent total dose degradation. There are some major hardness assurance considerations that can be drawn from this data.

Where ionization and displacement effects are independent, one can decouple the two phenomena and either test separate samples and combine data or use the same samples. Test data on parts that have been neutron and then total dose exposed can be used to evaluate lots that are going into orbits where displacement levels are low, such as geosynchronous. However, for half of the devices in this study, such an approach will significantly underestimate total dose degradation. For these parts a different approach is demanded.

A thorough characterization is necessary before deciding on an appropriate RLAT regimen. Where a part will be used in several environments, such as both a geo orbit and a much lower orbit where displacement fluences are significant, it is necessary to test some samples with gammas only and with neutrons and then gammas. The lot-to-lot variability observed for some parts suggests that samples from more than one lot should be used. Where neutron effects are comparable or larger than total dose effects at the levels of concern, one can expect synergistic effects will occur.

References:

1. Military Handbook 814, "Ionizing Dose and Neutron Hardness Assurance Guidelines for Microcircuits and Semiconductor Devices", see for example section 5.8.14 1994
2. J. Raymond and E. Peterson "Comparison of Neutron, Proton and Gamma Ray Effects in Semiconductor Devices", IEEE Transactions on Nuclear Science, Vol NS-34, No. 6 1987
3. H. Barnaby, R. Schrimpf, A. Sternberg, V. Berthe, C. Cirba, R. Pease, "Proton Radiation Response Mechanisms in Bipolar Analog Circuits", ", IEEE Transactions on Nuclear Science, Vol 48, 2001
4. H. Barnaby, S. Smith, R. Schrimpf, D. Fleetwood, R. Pease, "Analytic Model for Proton Radiation Effects in Bipolar Devices", IEEE Transactions on Nuclear Science, Vol 49, 2002
5. B. Rax, A. Johnston, T. Miyahara, "Displacement Damage in Bipolar Linear Integrated Circuits" ", IEEE Transactions on Nuclear Science, Vol 46, 1999
6. B. Rax, A. Johnston, C. Lee, "Proton Damage Effects in Linear Integrated Circuits", IEEE Transactions on Nuclear Science, Vol 45, 1998
7. H. Barnaby, R. Schrimpf, R. Pease, P. Cole, T. Turflinger, J. Krieg, J. Titus, D. Emily, M. Gehlhausen, S. Witczak, M. Maher, D. Nort, "Identification of Degradation Mechanisms in a Bipolar Linear Voltage Comparator Through Correlation of Transistor and Circuit Response" IEEE Transactions on Nuclear Science, Vol 46, 1999
8. H. Barnaby, C. Cirba, R. Schrimpf, D. Fleetwood, R. Pease, M. Shaneyfelt, T. Turflinger, J. Krieg, M. Maher, "Origins of Total-Dose Response Variability in Linear Bipolar Microcircuits" IEEE Transactions on Nuclear Science, Vol 47, 2000
9. A. Johnston and R. Plaag, "Model for Total Dose Degradation of Linear Integrated Circuits" IEEE Transactions on Nuclear Science, Vol 34, 1987

Table 1. Neutron vs Total Ionizing Dose Comparison*

P/N	Vendor	Database	Neutron Level n/cm^2	Neutron vs TID Effects – Exhibits Decreased TID Sensitivity?		Comments
LM111	National	98XX, 99XX date codes. 2 diffusions with parts from the same wafer	2E12	**Neutron** shifts were higher than TID shifts	**YES**	TID shifts after neutron irradiation increase than decrease. TID only, degrades monotonically. Effects saturate quickly. Other diffusions show similar behavior. **Figure 1.**
LM124	National	4 diffusions, 92-98XX date codes	6E11 - 2.5E12	**Neutron** shifts were higher than TID shifts	**YES**	Shifts are << spec limit for TID and ~ spec for 2E12 n/cm^2**. Figure 2**.
LM139	National	3 diffusions, 94-98XX date codes	6E11 - 2E12	**Neutron** shifts varied from lot to lot but were generally a little higher than the total dose shifts at the highest dose level	**Minimal**	Slightly more degradation for total dose only parts for two lots. One diffusion, neutron irradiated parts are slightly more sensitive. Effect is small in all cases
OP-01	Analog Devices (AD)	Only one diffusion with both. dc94XX	2E12	**TID** shifts exceeded neutron shifts even at 30 krads.	**NO**	TID only parts degraded slightly less than TID + N.
OP08/12	AD	7 diffusions. dc94XX-98XX	6E11 - 2E12	**TID** exceeded neutron shifts even at low total doses	**NO**	No difference. Large wafer to wafer variation seen within a single diffusion.
OP-11	AD	2 diffusions dc93XX, 96XX	6E11	**TID** shifts exceeded neutron shifts even at low total doses	**NO**	No difference seen
OP15/16	AD	4 diffusions dc96XX-00X	6E11 – 6E12	**TID** shifts exceeded neutron shifts even at low total doses	**NO**	No differences, but large scatter in some of the data. Neutron effects are generally small
OP-27	AD	3 diffusions dc97XXX-00XX	2E12	**TID** shifts are larger and in opposite direction to neutron shifts.	slight	Neutron irradiated parts show slightly more degradation, just greater than one standard deviation. Significant variation from part to part**. Figure 3.**
OP-471	AD	5 diffusions dc95XX-00XX	2E12	**TID** shifts exceed neutron shifts, significantly at higher levels	**NO**	No significant difference. Lot to lot variation was a factor of three in shifts at higher total dose levels.
OP-484	AD	2 diffusions dc98XX, 00XX	2E12	**TID** shifts exceed neutron degradation. They are comparable at the lowest doses. At higher levels tid shifts are 2-3 times higher	**YES**	Parts in one lot that were only TID exposed degraded much more than parts that were first neutron irradiated. A second lot showed no difference. Neutron shifts were quite close for the two lots. TID shifts were more varied. **Figure 4**.
RH1014	Linear Tech	3 diffusions dc98XX-01XX	4E11 – 1E12	**Neutron** shifts were greater than total dose shifts	**YES**	Total dose only parts show greater degradation. The most significant difference was for the lot that showed the most neutron degradation of the three. **Figure 5**
RH1056	Linear Tech	2 diffusions dc96XX, 98XX	2E12	**Neutron** shifts were greater than total dose shifts for one lot and comparable on a second lot at the highest dose	See comments	Above 100 krads, one lot shows a definite difference. A second lot shows very different behavior**. Figure 6.**

*Bias current. Total dose exposures were done at standard lab dose rates (50-300 r/s)

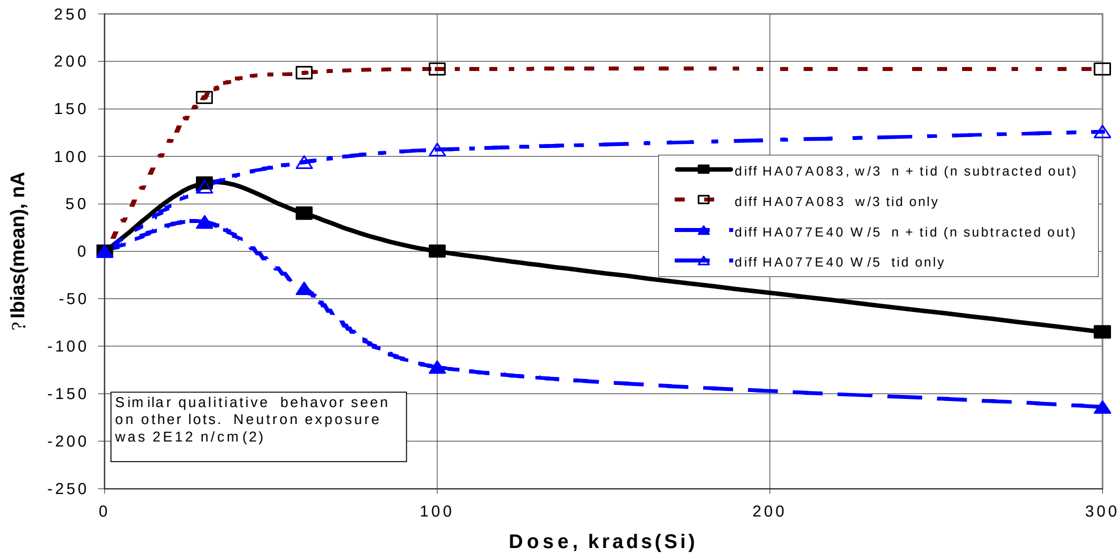

Figure 1. LM 111 Degradation

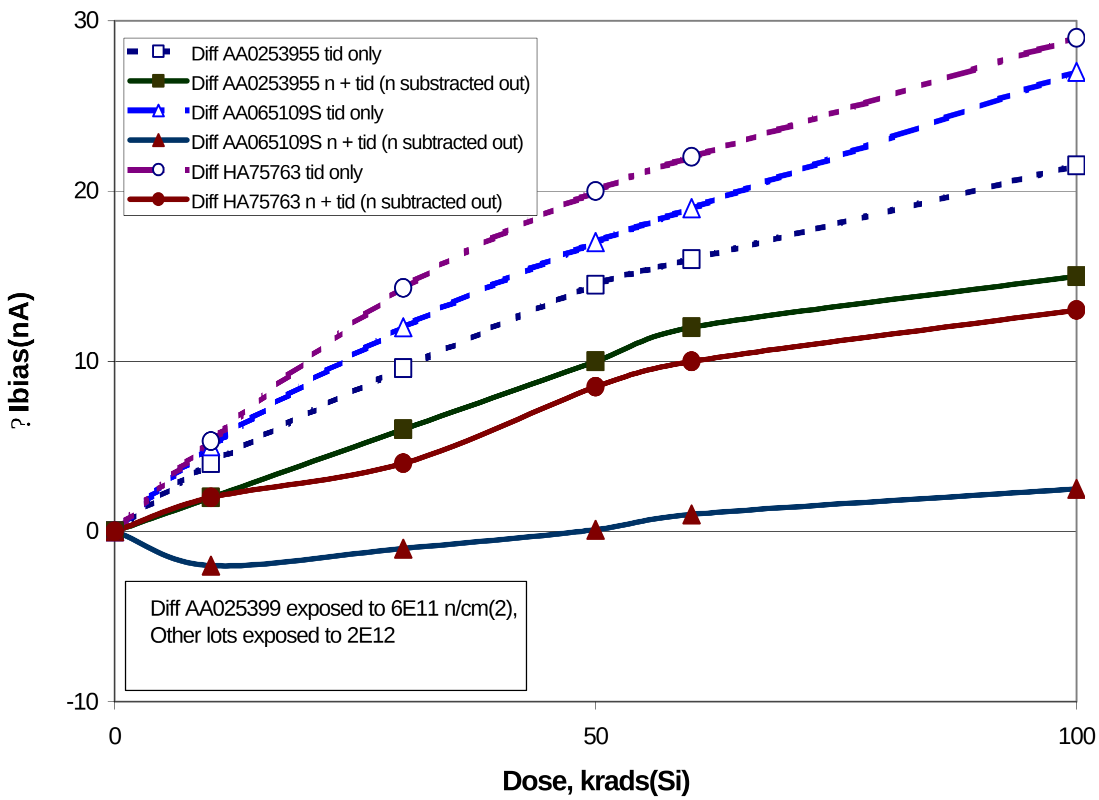

Figure 2. LM 124 Radiation Degradation

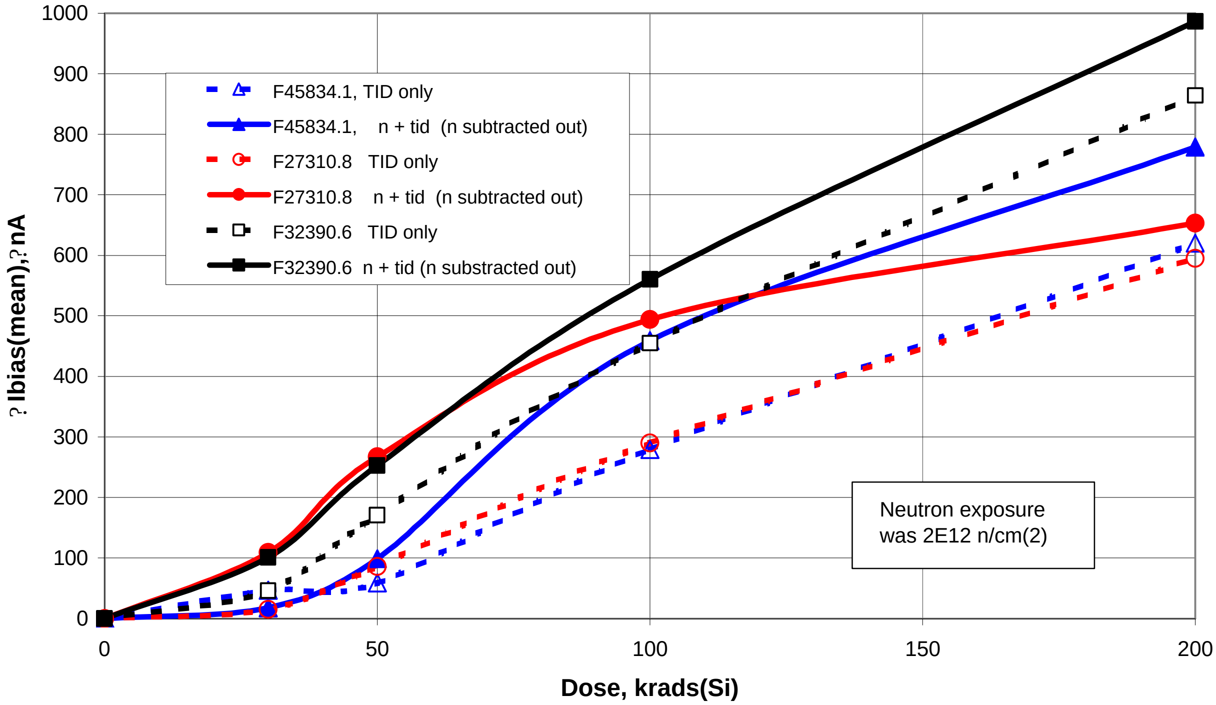

Figure 3. OP-27 Radiation Degradation

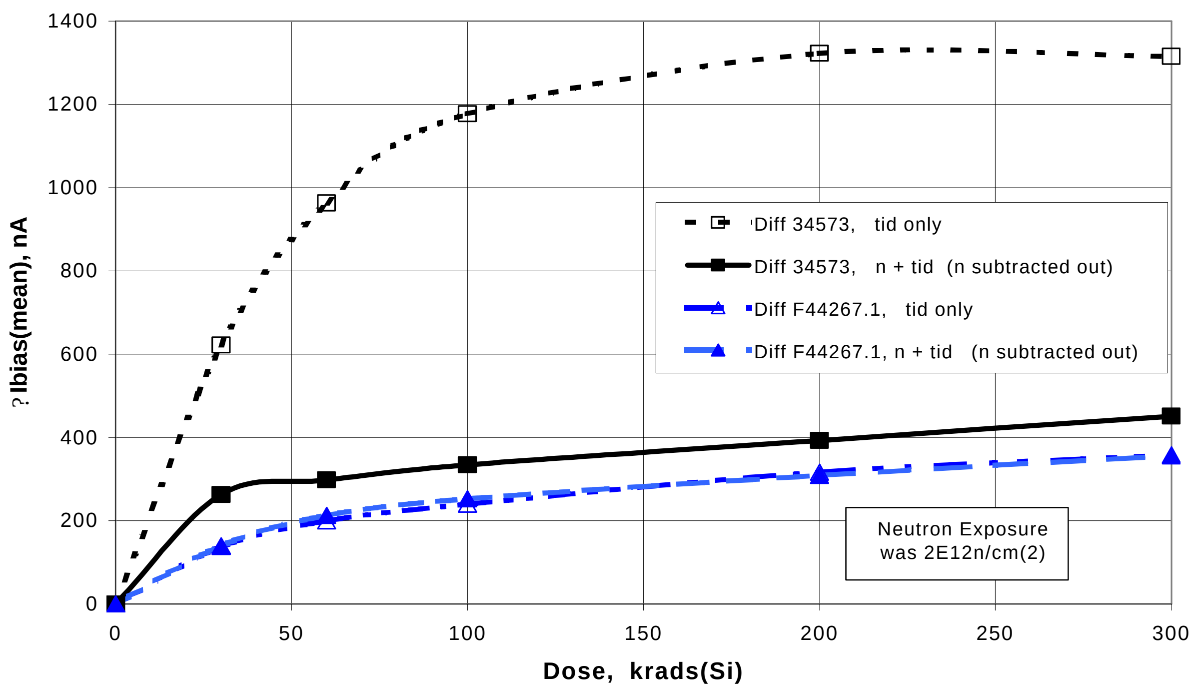

Figure 4. OP-484 Radiation Degradation

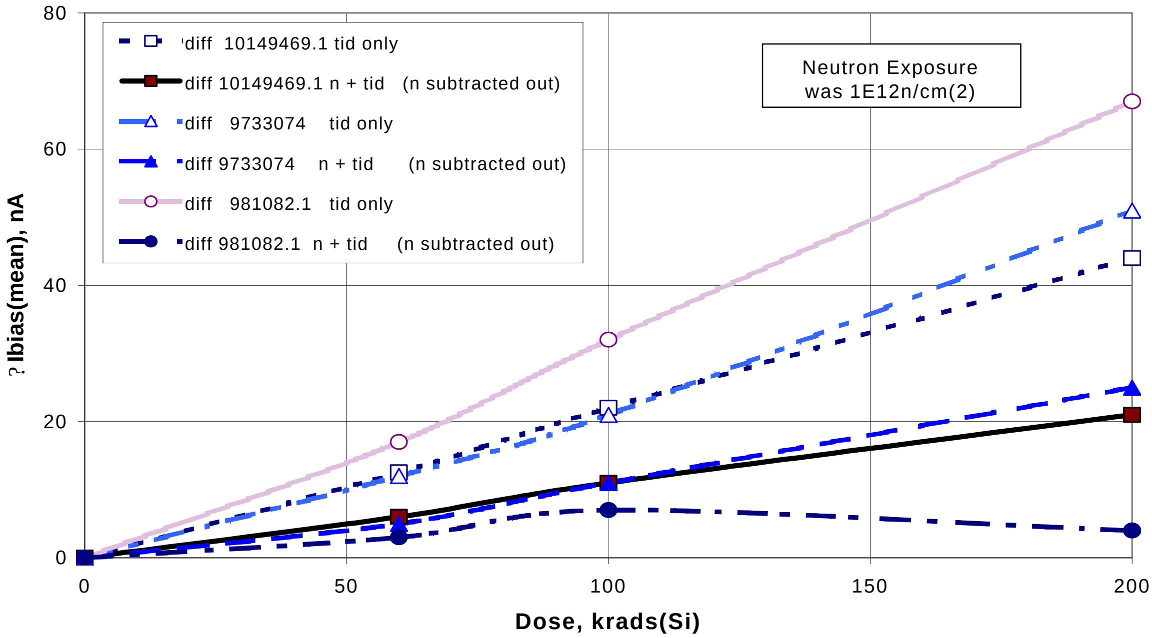

Figure 5. RH1014 Radiation Degradation

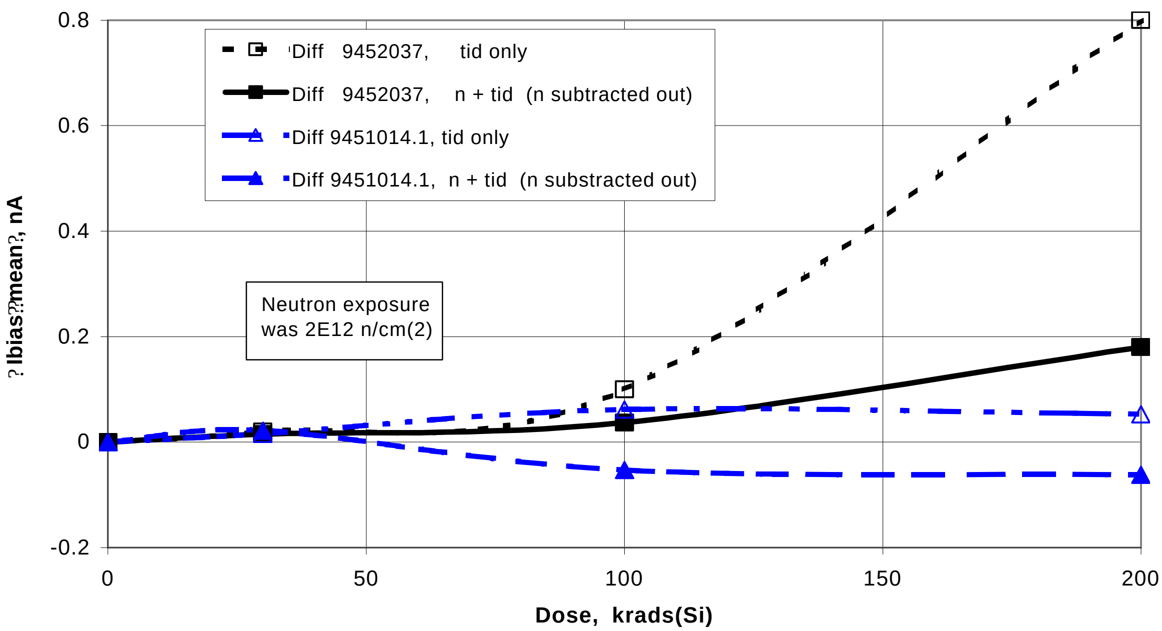

Figure 6. RH 1056 Radiation Degradation